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I. NEXT-STEP OPTION DESIGN STUDIES (DOE GRANT ER54350)

A. *FUSION TRANSMUTATION OF NUCLEAR WASTE*

We are investigating the potential applications of fusion neutron sources to 'drive' sub-critical fission reactors to perform one or more possible 'nuclear' missions. Our work indicates that since only a fraction of the neutrons in these applications would be fusion neutrons, the requirements are modest relative to the requirements for pure fusion electrical power (e.g. for the transmutation mission-- fusion power $P_{fus} \leq 250$ MW, fusion power density $\beta_N \leq 2.5$, 14 MeV neutron wall load $\Gamma_n < 1$ MW/m^2 and power amplification $Q_p \leq 2$). We believe on the basis of our studies that by making use of ITER physics and technology, using ITER as a prototype, and adopting the reactor and processing technology being developed in the nuclear program could lead to a fusion-driven sub-critical reactor for the transmutation of spent nuclear fuel, fissile breeding or disposition of weapons-grade plutonium being on-line by 2040, as compared to the plans for putting critical and accelerator-driven sub-critical reactors on-line for such missions by 2030. All of the R&D needed to develop the fusion neutron source for such a facility is directly on the path to fusion power (in fact is needed for an electric power DEMO); and the operation of a fusion-driven sub-critical reactor could also serve the purposes envisioned for a 'volume neutron source', thus taking the place of such a device in the development path to fusion power.

Tokamak Neutron Source Requirements

We have performed a series of systems studies[1-4] to examine whether a tokamak neutron source for a sub-critical transmutation reactor could be designed using the existing physics and fusion technology databases. Such a tokamak neutron source would be based on the ITER physics design basis and on the ITER first-wall, divertor, heating-current drive, tritium, etc. systems, but would likely use a liquid metal coolant for compatibility with the transmutation reactor and a ferritic steel structural material of the type being developed for nuclear applications. Two variants were examined—the FTWR (fusion transmutation of waste reactor) with copper magnet systems and the FTWR-SC with essentially the ITER superconducting magnet systems. A third variant based on advanced tokamak (AT) physics and the ITER superconducting magnet system—the FTWR-AT—was also examined. The principal parameters of such tokamak neutron sources are given in Table 1. The fusion powers shown in Table 1 correspond to the indicated value of β_N and the plasma volume; smaller values would result from operating at lower β_N.

Table 1 Tokamak Neutron Source Parameters for Transmutation Reactors

Parameter	FTWR[a]	FTWR-SC[b]	FTWR-AT[c]	ITER[d]
Fusion power, P_{fus} (MW)	≤ 150	≤ 225	≤ 500	410
Neutron source, S_{fus}(10^{19} #/s)	≤ 5.3	≤ 8.0	≤ 17.6	14.4
Major radius, R (m)	3.1	4.5	3.9	6.2
Minor radius, a (m)	0.9	0.9	1.1	2.0
Elongation, κ	1.7	1.8	1.7	1.8
Current, I (MA)	7.0	6.0	8.0	15.0
Magnetic field, B (T)	6.1	7.5	5.7	5.3
Confinement, H(y,2)	1.1	1.0	1.5	1.0
Normalized beta, β_N	≤ 2.5	≤ 2.5	4.0	1.8
Plasma Power Mult., Q_p	≤ 2.0	≤ 2.0	4.0	10
Electric Power Mult, Q_e	1	5		
Current-drive effic. η_{cd}	0.03	0.024	0.05	
" , γ_{cd} (10^{-20} A/Wm^2)	0.19	0.20	0.28	
Bootstrap I fraction, f_{bs}	0.67(0.38)[e]	0.56(0.24)	0.25	
Neut. flux, Γ_n (MW/m^2)	≤ 0.8	≤ 1.0	≤ 1.7	0.5
Heat flux, q_{fw} MW/m^2)	≤ 0.4	≤ 0.3	≤ 0.5	0.15
Availability (%)	≥ 50	≥ 50	≥ 50	

[a] ITER physics, liquid nitrogen cooled copper magnets.(Ref. 2)
[b] ITER physics, superconducting magnets. (Ref. 3)
[c] AT physics, superconducting magnets. (Ref. 4)
[d] ITER design parameters. (Ref. 5)
[e] required (estimated from present database)

For the FTWR and FTWR-SC, the requirements on β_N and confinement are within the present experimental range, and the requirements on β_N, confinement, energy amplification Q_p, and fusion power level are at or below the ITER level. The requirement on the combination of current-drive efficiency and bootstrap current fraction is beyond what has been achieved to date, but is certainly within the range envisioned for AT operation and may be achieved in ITER. Actually, the advanced current drive capability is the only AT operating capability that is needed or that can be taken advantage of for a fusion neutron source for the transmutation mission.

The configuration of the three FTWR concepts is depicted in Fig. 1. The sub-critical reactor is in the form of an annulus 40 cm thick by 228 cm high that wraps about the outboard side of the plasma chamber. This reactor is composed of fast reactor fuel assemblies containing 0.6 cm pins of a zirconium alloy containing transuranics from the SNF dispersed in a zirconium matrix. The reactor coolant is a lithium-lead eutectic enriched in ^{6}Li to achieve tritium self-sufficiency. A reflector and shield are located inboard of, above, and below the plasma chamber and above, below and outboard of the reactor to protect the magnets from radiation damage and to reflect neutrons towards the reactor. The magnet systems for the FTWR used oxygen-free high conductivity copper conductor and liquid nitrogen coolant, and the magnet systems for the FTWR-SC and FTWR-AT used Nb_3Sn and NbTi conductor cooled by supercritical helium.

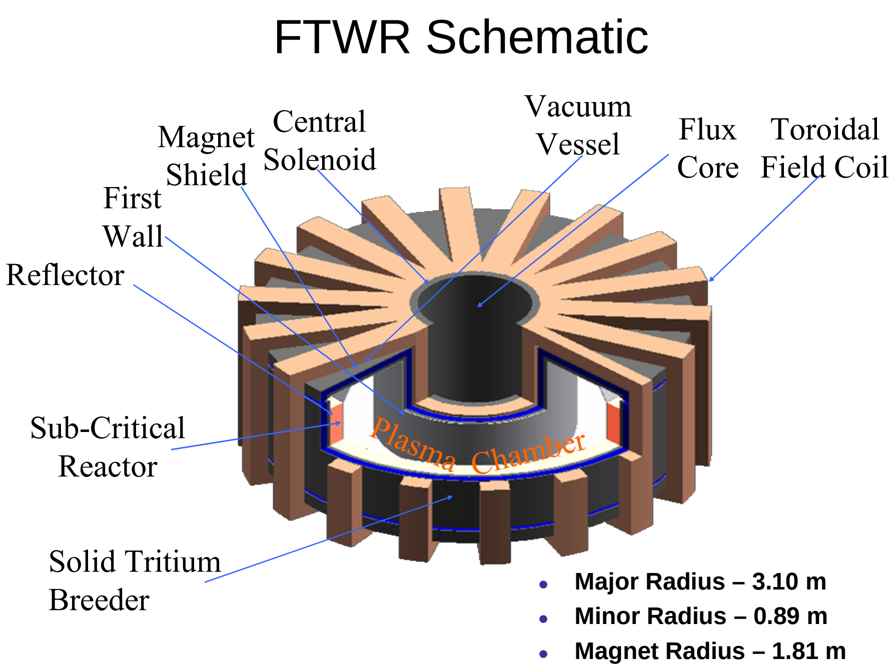

Figure 1 : Tokamak Fusion Transmutation of Waste Reactor

Nuclear Analysis

The nuclear transmutation reactor used for these studies was a metal fueled, Pb-Li cooled fast reactor adapted from an Argonne National Laboratory design of a transmutation reactor. We carried out a series of calculations to confirm the nuclear performance and to evaluate the safety characteristics of this reactor in the configuration of Fig. 1. These results[6] indicated that a subcritical reactor may be able to operate with a purely transuranic fuel, which would result in a higher net transmutation rate than a critical reactor operating at the same power level (because of the necessity of including U-238 to provide negative reactivity feedback in a critical reactor but also to cause the production of additional transuranics).

Comparative nuclear transmutation fuel cycle analyses of the FTWR, of a similar accelerator-driven sub-critical reactor, and of a similar critical reactor (but with U-238 included in the fuel) were performed[7]**.** The two subcritical reactors were found to have better overall transmutation performance than the critical reactor.

Incorporation of Transmutation Mission into the Fusion Development Program

The transmutation mission can be carried out with a tokamak fusion neutron source based on physics (H, β_N, Q_p, etc.) similar to or less demanding than that used for the ITER design, so the R&D program supporting ITER and the electrical power development mission will suffice for a transmutation neutron source in most physics areas. However, the transmutation neutron source would need to achieve a higher bootstrap current fraction and/or higher current drive efficiency and to achieve quasi-steady state operation in order to achieve higher availability than ITER. These issues must be addressed prior to the DEMO in the electrical power development path, but would have a higher relative priority in a physics R&D program for the transmutation mission.

The transmutation fusion neutron source can be constructed with the fusion technology being developed for ITER, for the most part, so the technology R&D supporting ITER will also support the fusion neutron source. However, the fusion neutron source will need to achieve greater availability, hence have greater component reliability, than ITER. The issue of component reliability, which will require various component test facilities, must be addressed prior to the DEMO in the electric power development path, but would have a higher relative priority in a technology development program to support the transmutation mission.

The reactor technology for the sub-critical reactor driven by the fusion neutron source should logically be adapted from the reactor (nuclear, fuel, cooling, processing, materials) technologies being investigated in the nuclear program (e.g. those being considered in the Generation–IV[8] and other such studies), but these technologies must be modified to provide for the tritium breeding requirement. A fusion nuclear technology program would have to be revived with this goal. There is a need to develop a long-lived structural material, primarily for the fuel assemblies of the sub-critical reactor but also for the first wall of the fusion neutron source, but it may be possible to build the initial transmutation fusion neutron sources with austenitic stainless steel first walls.

The technical requirements for a tokamak fusion neutron source that would fulfill the transmutation mission are significantly less demanding than for an economically competitive tokamak electrical power reactor, as indicated in Table 2. The first such neutron source could be built immediately following ITER, either before or in parallel with a fusion electrical power demonstration reactor (DEMO), which would have more demanding technical requirements on β_N, confinement and Q_p.

A more comprehensive systems/conceptual design investigation of the application of fusion to the transmutation mission is planned to further evaluate the possibility of incorporating a transmutation mission into the fusion development program. Evaluation of the competitiveness of sub-critical reactors driven by fusion neutron sources for the transmutation of SNF and of the required R&D would be the objectives of these studies. These investigations will initially be based on the most developed tokamak confinement concept (using the ITER physics and technology databases) and on adaptation of the reactor technology being developed in the nuclear program. Such studies will be coordinated with the GEN-IV nuclear fuel cycle studies[8].

We intend to next investigate a gas-cooled fast transmutation reactor using the TRISO fuel pellet that will be further developed in the nuclear program[11]. This type of fuel provides the potential for achieving almost complete transmutation of the actinides in spent nuclear with a minimal number of separation and reprocessing steps.

Table 2 Requirements for a Tokamak Neutron Source for a Transmutation Reactor, for an Economically Competitive Fusion Electric Power Tokamak Reactor and for a Tokamak DEMO

Parameter	Transmutation	Electric Power[a]	DEMO[b]
Confinement H(y,2)	1.0	1.5-2.0	1.5-2.0
Beta β_N	< 2.5	> 5.0	> 4.0
Power Amplification Q_p	< 2	≥ 50	> 10
Bootstrap Current Fraction f_{bs}	0.2-0.4	0.9	0.7
Neutron wall load (MW/m^2)	< 1.0	> 4.0	> 2.0
Fusion Power (MW)	≤ 200	3000	1000
Pulse length/duty factor	long/steady-state	long/steady-state	long/steady-state
Availability (%)	≥ 50	90	≥ 50

[a] ARIES studies (Ref. 9); [b] DEMO studies (Ref. 10)

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B. FUSION IGNITION RESEARCH EXPERIMENT

(J. Mandrekas)

During FY2003, the Georgia Tech Fusion Research Center continued its participation in the physics design activities of the Fusion Ignition Research Experiment (FIRE). Our main focus has been transport simulations with our 1½-D main plasma – multi charge state impurity transport code GTWHIST[1], in order to evaluate the impact of impurity seeded operation on the performance of FIRE.

While the new FIRE divertor design[2] can withstand the anticipated heat loads from the plasma core during the standard ELMy H-mode operation of the device, enhanced radiation from seeded impurities from the plasma mantle and the divertor is expected to be necessary during the higher power Advanced Tokamak (AT) operating mode in order to maintain a flexible operating space.

As a first step, the entire[*] FIRE reference operating scenario was modeled with GTWHIST and compared to the reference TSC simulation[3]. The results of this benchmarking simulation are shown in Fig,2, where time histories of various global power quantities are plotted. A fixed-shape transport model normalized to yield an H-factor of about 1 relative to the ITER IPB(y,2) global confinement scaling was adopted for these simulations.

[*] Since the MHD part of the GTWHIST code supports fixed-boundary configurations only, our simulation starts when the plasma geometry and fields (major and minor radii and toroidal magnetic field) are at their reference values, corresponding to about 4 seconds in the TSC simulation.

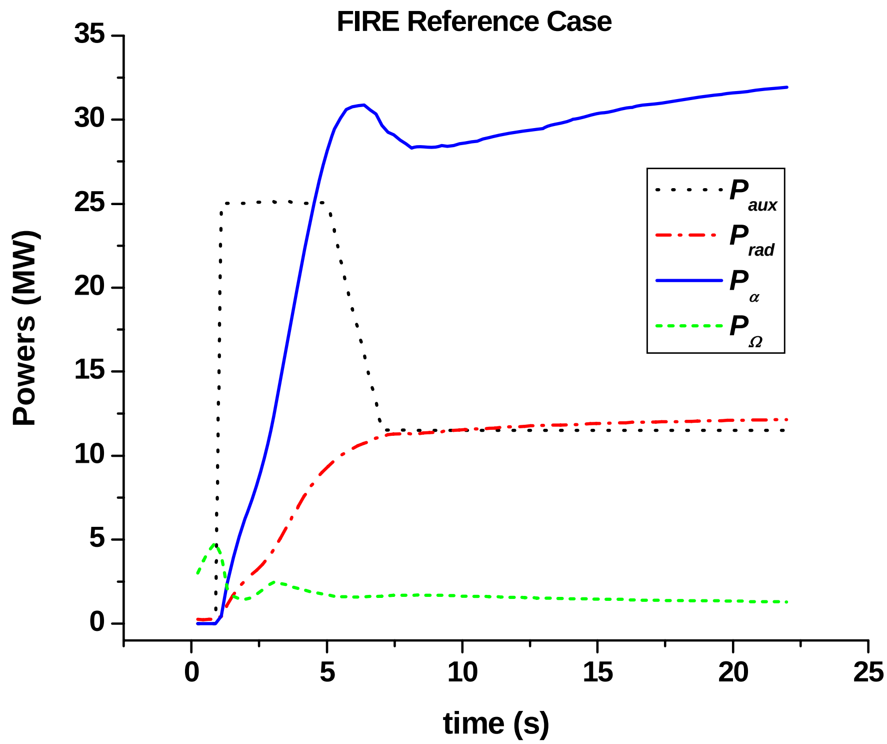

Figure 2: GTWHIST evaluation of the time history of various global power balance parameters for the FIRE reference case.

Following the establishment of the reference discharge, Argon impurities were injected at the edge of the device and their evolution and contribution to the power balance were followed using the multi-charge state impurity transport capabilities of the GTWHIST code. A fixed diffusion coefficient of 0.5 m^2/s for all impurity charge states and no inward pinch have been assumed in these simulations. The profiles of the various Ar charge states are shown in Fig. 3, for a 0.3% global Ar concentration.

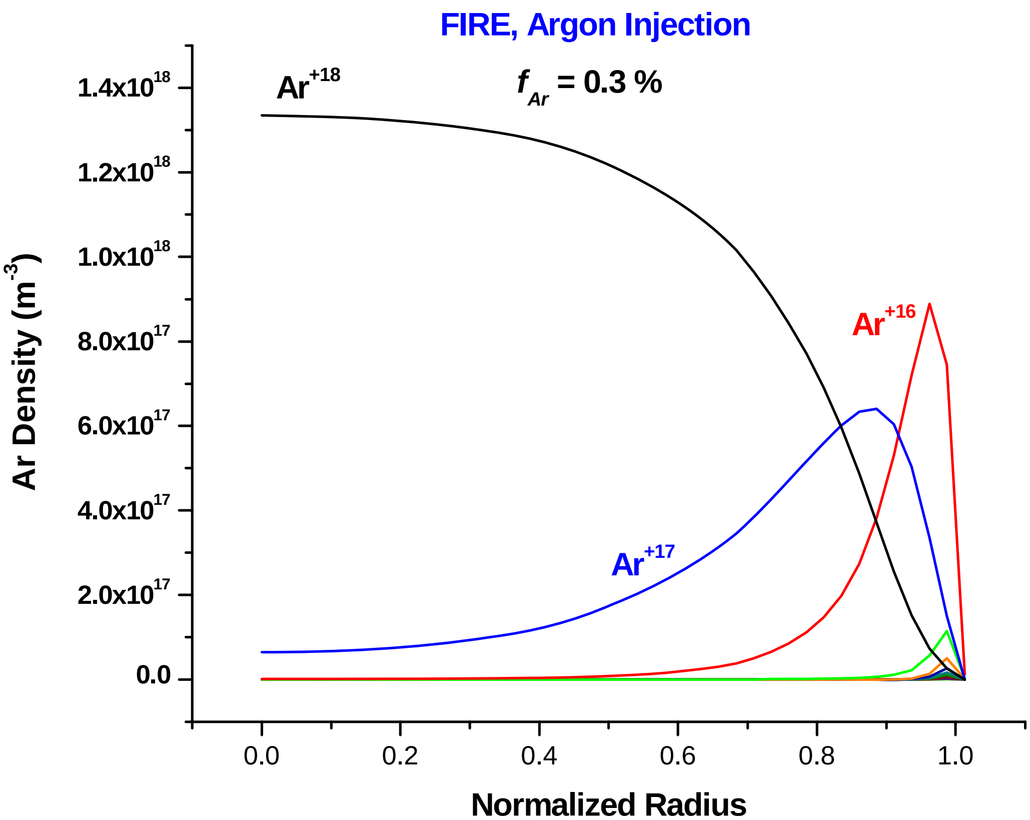

Figure 3: Profiles of Argon charge states following Ar injection.

As expected, Ar is almost fully ionized in the plasma core, while the highly radiating Lithium-like and Helium-like charge states are concentrated in the plasma edge. Our simulation predicts that for the reference concentration of 0.3%, the total radiated power by the Ar impurities (including bremsstrahlung and line radiation) is 45.2 MW, which is about 20%-30% higher than the predictions of earlier 0-D (fixed profiles) simulations. This suggests that lower Ar concentrations may be adequate to meet the needs of the FIRE design.

In addition to the determination of the radiating properties of the seeded Ar impurities, our simulations identified a number of critical issues that must be addressed before impurity seeding can be safely adopted as part of the reference operating scenario of FIRE. These include: a) the potential of edge thermal instabilities following Ar injection which were observed in several of our simulations and which can collapse the edge temperature profile and, eventually, terminate the plasma; b) the sensitivity of our predictions to the edge temperature assumptions, underlying the need for a realistic and accurate pedestal boundary condition model; c) the importance of the edge ion and electron thermal transport assumptions; and d) the possibility of core impurity accumulation due to neoclassical effects arising from peaked density profiles. These issues will be examined in detail during our FY2004 FIRE work.

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3. C. Kessel, PPPL, personal communication, Dec. 2003.

C. SUPPORT FOR NTCC ACTIVITY

(J. Mandrekas)

During FY 2003, we continued our participation in the National Transport Code Collaboration (NTCC) activity. We completed the review of the neutral transport module NUT (P. Valanju, IFS) and are in the process of upgrading the Lower Hybrid module LSC (D.W. Ignat, PPPL) with the addition of trapped electron effects. The upgraded module will be benchmarked against lower hybrid current drive simulations by P. Bonoli of MIT, and will then be resubmitted to the NTCC for eventual review and acceptance in the module library.